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AN INTERLABORATORY PHOTOMETRIC COMPARISON OF GLASS SCREENS AND OF TUNGSTEN LAMPS, INVOLVING COLOR DIFFERENCES

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I. INTRODUCTION

Since the establishment of the international candle in 1909 this unit has been maintained at the Bureau of Standards solely by means of a group of 4-wpc carbon filament incandescent lamps. With the advent of the tungsten lamp there was introduced into standardization work the difficulty of comparing lights of different colors, and at once it became desirable to have the unit well established also in tungsten lamps operated at or near their normal color.

In 1911, by common agreement between the National Physical Laboratory of England and the Bureau of Standards, each laboratory prepared a group of tungsten standards calibrated for voltage corresponding to approximately 1.5 wpc. These two groups of lamps, which were thus operated at very approximately the same color, were then exchanged and each group was remeasured by the receiving laboratory at the voltage determined by the sending laboratory. A group, similar to the one sent to England, and standardized in the same series of measurements,

was retained at the Bureau, and half of the group received from England, after measurement, was returned for remeasurement.

In view of the difficulties involved in the intercomparison, the result was very satisfactory, as it showed that the two laboratories were in agreement to within the indicated precision of the measurements. In both laboratories the new standards were measured by means of Lummer-Brodhun contrast photometers of the standard type, and in terms of similar groups of 4-wpc carbon standards, the English laboratory having made the comparison by the cascade method,¹ the Bureau of Standards by the use of two calibrated blue glass screens, each of which produced a color match between the two groups of standards compared. It is obvious, therefore, that the calibration of the glass screens used by the Bureau in this intercomparison was a matter of prime importance, and for this reason a large amount of work has been done in checking, by various methods, the values first assigned.

In connection with these check measurements and after a determination of the candlepower and current of a group of tungsten substandards at several voltages had been made, and this followed by a further investigation of other groups of tungsten lamps, the voltage-current-candlepower curves were determined and accurately expressed by means of equations.² It was found that by employing these equations it is possible to measure tungsten lamps in color match with 4-wpc carbon standards and compute with accuracy their value at any other color within the range investigated. In this way, as well as by direct comparisons, the new tungsten standards have been rechecked a number of times by different groups of observers.

These equations have an important application also in the life testing of tungsten lamps, because in some testing laboratories it is customary to photometer the lamps at or near rated voltage and compute the voltage corresponding to the efficiency at which it is desired to burn the lamps on life test.

In the establishment of the 1.5-wpc tungsten standards and also in the determination of the characteristic equations, the photometric measurements of necessity involved color differences. Although numerous check measurements have been made and the results have been very satisfactory, it is, of course, realized

¹ Paterson and Dudding, Proc. Phys. Soc. London, p. 263, Apr. 15, 1915; also Phil. Mag., p. 63, July, 1915.

² Middlekauff and Skogland, Characteristic Equations of Tungsten Filament Lamps and their Application in Heterochromatic Photometry, Trans. I. E. S. 9, p. 734, 1914; also this Bulletin, 11, p. 483, 1915.

that if some other group of observers had made these measurements the values obtained might have been different.

It was therefore suggested that an interlaboratory photometric comparison of lights involving color differences such as those encountered in these measurements would yield valuable information not only as to the agreement which might be reasonably expected among different groups of experienced observers, but also information as to the merits of different methods of making such measurements.

II. LABORATORIES COOPERATING

The Bureau, therefore, in May, 1914, invited several of the more important photometric laboratories of the country to cooperate with it in making measurements of this kind.

Through Dr. E. P. Hyde, Dr. C. H. Sharp, and Dr. H. E. Ives, respectively, the Nela Research Laboratory, the Electrical Testing Laboratories, and the Physical Laboratory of the United Gas Improvement Co. kindly agreed to make such measurements on glass screens and tungsten lamps as the Bureau would direct.

III. SCREENS, LAMPS, AND INSTRUCTIONS AS TO METHODS OF MEASUREMENT

For this intercomparison there were selected three blue glass screens of different color densities and marked 2B, 2½B, and 3B, respectively. 2½B was of approximately the same color density as the screens used by the Bureau in the intercomparison with England, and was therefore such as to produce a color match between the 4-wpc carbon standards and the 1.5-wpc tungsten standards. 2B and 3B were of lesser and greater color density, respectively, than 2½B, producing a color match between the 4-wpc carbon standards and tungsten lamps at about 1.9 wpc and 1.25 wpc, respectively.

The transmission of each glass for light of 4-wpc carbon color was to be determined by each laboratory, and, in order that the proper color might be used, a carbon standard of this color at a specified voltage was sent along with the screens.

There were selected also four tungsten standards to be measured for candlepower and current at several specified voltages, the color at the lowest voltage being the same as that of the 4-wpc carbon standards. The candlepower at the other voltages was to be determined in terms of the value at the lowest voltage taken as standard, or unity.

The voltages specified for these measurements corresponded to a range from 3.1 wpc to 0.85 wpc for the tungsten lamp. The lamps were selected from those used in the investigation of the characteristic curves and included a 60-watt sintered filament lamp (No. 2608); a 60-watt "formed" drawn-wire lamp (No. 2662) with spring anchors; and two 40-watt drawn-wire lamps (Nos. 2865 and 2866).

As the purpose of the investigation was to obtain information as to methods and the agreement of different groups of observers in passing from one color to another in photometric measurements, no instructions other than those mentioned above were issued to the laboratories. It was desired that each laboratory proceed by the method it considered best, and it was not expected that a large number of measurements would be made. Hence, in view of the difficulties which were to be met in these measurements, it was hardly to be expected that values established by the Bureau as the result of a much larger number of measurements and checks would be repeated exactly. However, as will appear later, the results of all the laboratories are extremely consistent and the agreement quite satisfactory.

Two of the laboratories (E. T. L. and N. R. L.) used standard type Lummer-Brodhun contrast photometers in all the measurements. The third laboratory (U. G. I.), in the measurements on the screens, used a special flicker photometer,³ and in the measurements on the lamps a Lummer-Brodhun photometer having in the eyepiece a cell containing a Crova solution⁴ which was calibrated by a method involving the flicker photometer. All the measurements by the U. G. I. were made under selected conditions of illumination and with groups of observers selected after tests of their color vision with respect to the average of much larger groups. The data obtained are therefore valuable in making a comparison, not only of observers but also of different methods of measurement.

In no laboratory were the lamps measured at the same time as the screens, a period of from 4 to 13 months having intervened between the two series.⁵ Although this was not intentional, it fortunately proved of value in showing that each laboratory consistently maintained its criterion in measurements involving a

³ H. E. Ives, Phys. Rev., p. 222; Sept., 1914.

⁴ Ives and Kingsbury; Trans. I., E. S., 10, p. 716; 1915.

⁵ The intercomparison was begun in June, 1914, but was not completed until in December, 1915.

color difference. In order to avoid confusion, all the results, including those of the Bureau, on the screens are given together, as are likewise the results on the lamps.

IV. RESULTS ON THE SCREENS

The values for the screens are given in the four following tables, and, except as noted, they are as stated in the reports from the laboratories. The results of the three laboratories using Lummer-Brodhun photometers are grouped together, and when comparisons are made, flicker values are compared with the mean of those obtained with the Lummer-Brodhun.

TABLE I
Values of Transmission—Bureau of Standards

Observers	2B		2½B		3B	
	Indirect method	Direct method	Indirect method	Direct method	Indirect method	Direct method
G. W. M.....	0.652	0.654	0.585	0.588	0.537	0.542
J. F. S.....	.651	.652	.585	.584	.538	.538
B. M.....	.648	.645	.581	.575	.541	.526
H. B. S.....	.652	.667	(a)	.596	(a)	.552
W. J. K.....	.652	.652	.585	.580	.539	.534
W. H. V.....	.651	.648	.581	.581	.535	.535
A. H. T.....	.651	.655	.584	.583	.541	.535
G. J. S.....	.650	.652	.585	.582	.538	.536
Mean.....	.651	.653	.584	.584	.538	.537

^a Observer not available.

The photometer used was the standard Lummer-Brodhun contrast. The approximate illumination on the photometer screen was 10 meter-candles.

METHODS.—*1. Direct Method.*—The screen was placed on the test side of the photometer, the test lamp (a tungsten) was set to 4-wpc carbon color, and the comparison lamp (also a tungsten) was adjusted to match in color the light transmitted by the screen. Photometric settings were made first with the screen in place, then with it removed, there being a color difference under the latter condition. The ratio of the first settings to the second gave the transmission of the screen.

2. Indirect Method.—The first settings were made as in the direct method, but when the screen was removed the test lamp

was sufficiently increased in voltage to produce a color match with the comparison lamp. The ratio of the candlepower of the test lamp at these two voltages was computed by means of the voltage-candlepower equation. With this factor applied, the ratio of the settings, screen in to screen out, gave the transmission.

In both of the above methods, when the screen was removed it was replaced by a rotating sectored disk of the proper opening to make the photometer balance at about the same point as when the screen was in place.

Each value in Table 1 is the mean of about four independent determinations, the average deviation, by either method, being about 0.5 per cent.

TABLE 2

Values of Transmission—Electrical Testing Laboratories

Observers	2B			2½B			3B		
	Series 1	Series 2	Weighted mean	Series 1	Series 2	Weighted mean	Series 1	Series 2	Weighted mean
C. H. S.....	0.651	.....	0.651	0.583	.....	0.583	0.537	.....	0.537
W. F. L.....	.660	0.672	.666	.594	0.586	.590	.530	0.553	.542
M. H. T.....	.660	.662	.661	.585	.588	.586	.545	.546	.545
C. E. H.....	.656	.652	.655	.586	.587	.586	.545	.537	.542
W. A. M.....	.656	.657	.656	.587	.576	.583	.543	.539	.542
Z. N. C.....	.653	.....	.653	.579	.....	.579	.535	.....	.535
A. K.....	.659	.....	.659	.589	.....	.589	.539	.....	.539
E. H.....	.....	.666	.666	.....	.594	.594	.....	.555	.555
Mean.....	.656	.662	.....	.586	.586	.....	.539	.546	.....
Weighted mean.....	.656	.659	.657	.585	.586	.585	.541	.543	.542

The photometer used was the standard Lummer-Brodhun contrast. The approximate illumination on the photometer screen was 2.5 to 3.8 meter-candles. As the distance between test and comparison lamps was fixed, the illumination depended upon the screen used and was highest with the screen removed.

Method: Direct.—Two carbon lamps, each operated at a voltage giving a match in color with the B. S. 4-wpc carbon lamp, were set up at opposite ends of a five-meter photometer. Settings were made, first without the screen, then with the screen interposed. This was done first on one side of the photometer and then on the other. The observers were weighted according to their experience in color difference measurements and the number of measurements made in these tests. Series 1 and 2 are independent

determinations by this method. For purposes of comparison the weighted mean values (columns 4, 7, and 10) for each observer were computed by the authors.

TABLE 3
Values of Transmission—Nela Research Laboratory

Observers	2B			2½B			3B		
	Series 1	Series 2	Mean	Series 1	Series 2	Mean	Series 1	Series 2	Mean
E. P. H.....	.660	.662	.661	.590	.592	.591	.544	.543	.544
F. E. C.....	.659	.661	.660	.592	.590	.591	.548	.546	.547
M. L.....	.665	.660	.662	.593	.590	.592	.551	.541	.546
C. F. S.....	.652	.650	.651	.578	.578	.578	.531	.530	.531
R. G. B.....	.664	.662	.663	.594	.592	.593	.550	.549	.550
I. R. W.....	.656	.656	.656	.584	.584	.584	.540	.538	.539
Mean.....	.659	.658	.659	.588	.588	.588	.544	.543	.543

The photometer used was the standard Lummer-Brodhun contrast. The approximate illumination on photometer screen was 17 meter-candles.

Method.—Same as the B. S. direct method; except that the screen and sectored disk were employed on the side of the comparison lamp, which was set to 4-wpc carbon color. Series 1 and 2 are independent determinations by this method.

TABLE 4
Values of Transmission—United Gas Improvement Co.

Observers	2B			2½B			3B		
	Series 1	Series 2	Mean	Series 1	Series 2	Mean	Series 1	Series 2	Mean
H. E. I.....	.645	.650	.6475	.580	.579	.5795	.534	.527	.5305
E. F. K.....	.658	.661	.6595	.587	.588	.5875	.548	.543	.5455
F. A. S.....	.645	.646	.6455	.583	.577	.5800	.528	.523	.5255
B. J.....	.656	.642	.6490	.575	.574	.5745	.528	.528	.5280
D. V. L. D.....	.639	.642	.6405	.585	.578	.5815	.529	.522	.5255
E. J. B.....	.637	.639	.6380	.572	.573	.5725	.521	.522	.5215
W. M. W.....	.640	.643	.6415	.576	.577	.5765	.521	.528	.5245
Mean.....	.646	.646	.646	.580	.578	.579	.530	.528	.529

The photometer used was a special flicker (see footnote 3). The brightness of the photometer field was that of a magnesium oxide surface under 25 meter-candles illumination.

Method: Direct.—The measurements were made by seven observers so selected from 25 that their mean on the color difference for which they were tested was the same as that of the 25.

TABLE 5

Deviations of Each Observer From the Mean of His Laboratory

BUREAU OF STANDARDS

Direct Method

Observers	Transmission				Deviation of observers from mean of all			Mean of deviations	Maximum difference between deviations
	2B	2½B	3B	Mean	2B	2½B	3B		
G. W. M.....	0.654	0.588	0.542	0.595	+0.001	+0.004	+0.005	0.003	0.004
J. F. S.....	.652	.584	.538	.592	-.001	-.000	+.001	.001	.002
B. M.....	.645	.575	.526	.582	-.008	-.009	-.011	.009	.003
H. B. S.....	.667	.596	.552	.605	+.014	+.012	+.015	.014	.003
W. J. K.....	.652	.580	.534	.589	-.001	-.004	-.003	.003	.003
W. H. V.....	.648	.581	.535	.588	-.005	-.003	-.002	.003	.003
A. H. T.....	.655	.583	.535	.591	+.002	-.001	-.002	.002	.004
G. J. S.....	.652	.582	.536	.590	-.001	-.002	-.001	.001	.001
Mean.....	.653	.584	.537	.591	.004	.004	.005	.004	.003

Indirect Method

G. W. M.....	0.652	0.585	0.537	0.591	+0.001	+0.001	-0.001	0.001	0.002
J. F. S.....	.651	.585	.538	.591	.000	+.001	.000	.000	.001
B. M.....	.648	.581	.541	.590	-.003	-.003	+.003	.003	.006
H. B. S.....	.652	.....	.....	.....	+.001	.....	.....	.....	.....
W. J. K.....	.652	.585	.539	.592	+.001	+.001	+.001	.001	.000
W. H. V.....	.651	.581	.535	.589	.000	-.003	-.003	.002	.003
A. H. T.....	.651	.584	.541	.592	.000	.000	+.003	.001	.003
G. J. S.....	.650	.585	.538	.591	-.001	+.001	.000	.001	.002
Mean.....	.651	.584	.538	.591	.001	.001	.002	.001	.002

ELECTRICAL TESTING LABORATORIES (Direct Method)

C. H. S.....	0.651	0.583	0.537	0.590	-0.006	-0.002	-0.005	0.004	0.004
W. F. L.....	.666	.590	.542	.599	+.009	+.005	.000	.005	.009
M. H. T.....	.661	.586	.545	.597	+.004	+.001	+.003	.003	.003
C. E. H.....	.655	.586	.542	.594	-.002	+.001	.000	.001	.003
W. A. M.....	.656	.583	.542	.594	-.001	-.002	.000	.001	.002
Z. N. C.....	.653	.579	.535	.589	-.004	-.006	-.007	.006	.003
A. K.....	.659	.589	.539	.596	+.002	+.004	-.003	.003	.007
E. H.....	.666	.594	.555	.605	+.009	+.009	+.013	.010	.004
Mean.....	.657	.585	.542	.595	.005	.004	.004	.004	.004

TABLE 5—Continued

Deviations of Each Observer From the Mean of His Laboratory—Continued

NELA RESEARCH LABORATORY (Direct Method)

Observers	Transmission				Deviation of observers from mean of all			Mean of deviations	Maximum difference between deviations
	2B	2½B	3B	Mean	2B	2½B	3B		
E. P. H.....	0.661	0.591	0.544	0.599	+0.002	+0.003	+0.001	0.002	0.002
F. E. C.....	.660	.591	.547	.599	+.001	+.003	+.004	.003	.003
M. L.....	.662	.592	.546	.600	+.003	+.004	+.003	.003	.001
C. F. S.....	.651	.578	.531	.587	-.008	-.010	-.012	.010	.004
R. G. B.....	.663	.593	.550	.602	+.004	+.005	+.007	.005	.003
I. R. W.....	.656	.584	.539	.593	-.003	-.004	-.004	.004	.001
Mean.....	.659	.588	.543	.597	.003	.005	.005	.004	.002

UNITED GAS IMPROVEMENT CO. (Direct Method)

H. E. I.....	0.648	0.580	0.530	0.586	+0.002	+0.001	+0.001	0.001	0.001
E. F. K.....	.660	.588	.546	.598	+.014	+.009	+.017	.013	.008
F. A. S.....	.646	.580	.526	.584	.000	+.001	-.003	.001	.004
B. J.....	.649	.574	.528	.584	+.003	-.005	-.001	.003	.008
D. V. L. D.....	.640	.582	.526	.583	-.006	+.003	-.003	.004	.009
E. J. B.....	.638	.572	.521	.577	-.008	-.007	-.008	.008	.001
W. M. W.....	.642	.575	.524	.581	-.004	-.003	-.005	.004	.002
Mean.....	.646	.579	.529	.585	.005	.004	.005	.005	.005

(a) COMPARISON OF INDIVIDUALS' VALUES.—Another statement of the results, including only the mean of the values obtained by each observer on each of the three screens, is given in Table 5. In the fifth column is given the mean of the values of each observer for the three glasses. In the sixth, seventh, and eighth columns are the deviations of each observer's value from the mean of his laboratory on each glass. The constancy of the ratio of an observer's determination to that of his laboratory shows the consistency with which he maintains his criterion throughout the range of color included. An examination of the deviations shown in this table (excluding for the present those of the Bureau by the indirect method) shows that practically every observer, irrespective of the kind of photometer used, maintained a fairly definite relation to the mean of the observers of his laboratory. An observer's agreement with himself is indicated by the differences given in the last column of the table.

By the indirect method the variations among observers is avoided, the difficulties of measurements with a color difference having been previously met in the determination of the characteristic equation upon which, of course, the values obtained depend. As shown by the table, the deviations of all observers are about equal and about one-fourth what they are by the direct (color difference) method, although there is practically the same degree of agreement of an observer with himself. The chief advantage of this method in calibrating a screen is that a reliable result may be obtained by any group of observers, while by the direct method the results may be somewhat different, depending upon the characteristics of the observers.

(b) COMPARISON OF LABORATORIES' VALUES.—In order to show in the same way the agreement among the various laboratories, each taken as a unit, the final means for each laboratory are given in Table 6, in which, as before, the flicker values are compared with the mean of those obtained with the Lummer-Brodhun photometer.

TABLE 6

Deviations of Laboratories' Values from the Mean of the Three Using Lummer-Brodhun Photometers

Lummer-Brodhun Photometer

Laboratories	Transmission				Deviations from mean L-B values			Mean of devia- tions	Maxi- mum difference between devia- tions
	2B	2½B	3B	Mean	2B	2½B	3B		
B. S.....	0.653	0.584	0.537	0.591	-0.003	-0.002	-0.004	0.003	0.002
E. T. L.....	.657	.585	.542	.595	+ .001	- .001	+ .001	.001	.002
N. R. L.....	.659	.588	.543	.597	+ .003	+ .002	+ .002	.002	.001
Mean.....	.656	.586	.541	.594	.002	.002	.002	.002	.002

Flicker Photometer

U. G. I.....	0.646	0.579	0.529	0.585	-0.010	-0.007	-0.012	0.010	0.005
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V. RESULTS ON THE LAMPS

The results on the lamps were expressed differently by each laboratory. One (E. T. L.) gave all the values in candlepower; another (U. G. I.) reported the values as ratios using the value at the lowest voltage as unity; and the third (N. R. L.) gave the ratio of the candlepower at each voltage to the candlepower at the next lower voltage. Only one laboratory (N. R. L.) reported the values of the individual observers as was done by all in their reports on the screens. For this reason only the mean values obtained by each laboratory are given in the table of results (Table 7).

The Bureau's values of both current and candlepower were read from the characteristic curves previously determined by a group of observers whose mean was practically the same as the mean of the group that made the measurements on the screens.

In the Electrical Testing Laboratories the candlepower measurements were made by two observers (M. H. T. and C. E. H.) whose mean was the same as the mean of all the observers on the screens and the color steps were made with Wratten filters which had been calibrated by a large number of observers. In the Nela Research Laboratory the measurements on the lamps and screens were made by the same group of observers with the exception that observer M. L. made no measurements on the lamps. The cascade method was used in determining values on the lamps at the various voltages.

In the U. G. I. Laboratory the lamps were measured with a Lummer-Brodhun photometer having in the eyepiece a Crova solution calibrated on the photometric scale there used in which are involved the flicker photometer under certain chosen illumination and other conditions and the selection of observers from a large group. The group used as a basis for the Crova solution work consisted of 61 observers; the glass screen calibrations were on the basis of a group of 25.

TABLE 7

Candlepower and Current Values Found by the Different Laboratories

Lamp Nos.	Volts	Relative candlepower				Amperes			
		Lummer-Brodhun photometer			Flicker photometer	B. S.	E. T. L.	N. R. L.	U. G. I.
		B. S.	E. T. L.	N. R. L.	U. G. I.				
2608.....	71	1.000	1.000	1.000	1.00	0.3646	0.3647	0.3646	0.3650
	81	1.674	1.677	1.684	1.68	.3944	.3944	.3944	.3951
	91	2.604	2.616	2.627	2.60	.4224	.4229	.4226	.4234
	101	3.832	3.848	3.864	3.85	.4495	.4498	.4496	.4500
	111	5.392	5.434	5.460	5.34	.4753	.4758	.4756	.4757
	70	1.000	1.000	1.000	1.00	.3926	.3925	.3920	.3929
	80	1.687	1.695	1.696	1.69	.4245	.4249	.4244	.4253
2662.....	90	2.638	2.647	2.661	2.60	.4549	.4555	.4551	.4555
	100	3.896	3.923	3.931	3.88	.4843	.4846	.4840	.4844
	110	5.501	5.554	5.585	5.45	.5118	.5125	.5120	.5121
	72	1.000	1.000	1.000	1.00	.2625	.2628	.2626	.2625
	82	1.659	1.659	1.674	1.65	.2838	.2841	.2838	.2840
	92	2.567	2.579	2.615	2.56	.3037	.3041	.3036	.3035
	112	5.277	5.354	5.389	5.28	.3408	.3411	.3406	.3408
2865.....	132	9.40	9.45	9.58	9.22	.3744	.3752	.3748	.3749
	72	1.000	1.000	1.000	1.00	.2611	.2615	.2614	.2616
	92	2.576	2.588	2.621	2.58	.3020	.3024	.3024	.3024
	112	5.304	5.355	5.415	5.30	.3390	.3395	.3393	.3394
	122	7.191	7.223	7.321	7.16	.3562	.3568	.3566	.3566
	132	9.46	9.52	9.63	9.38	.3728	.3735	.3732	.3731

The Nela Research Laboratory gave the highest and lowest ampere values at each voltage, but to make the results uniform with the definite values reported by the other laboratories the mean of these extremes at each voltage was assumed as the correct ampere value. The deviations of the ampere values as given for the various laboratories in Table 7 from the mean of all at each voltage have been computed and found to be, on the average, about 0.05 per cent and the same for all four lamps.

In Table 8 are given the values of the ratios of the candle-power at each voltage to that at the lowest voltage, which corresponds to 4-wpc carbon color. The laboratories are arranged in the order in which they measured the lamps. As in the case of the results on the glass screens, the values obtained by each laboratory are compared with the mean of the three laboratories using Lummer-Brodhun photometers.

TABLE 8

Comparison of Candlepower Ratios Found by the Different Laboratories

Lamp Nos.	Voltage ratio	Candlepower ratio				
		Lummer-Brodhun photometer				Flicker photometer
		B. S.	E. T. L.	N. R. L.	Mean	
2608.....	81:71	1.674	1.677	1.684	1.678	1.68
2662.....	80:70	1.687	1.695	1.696	1.693	1.69
2865.....	82:72	1.659	1.659	1.674	1.664	1.65
Mean.....		1.673	1.677	1.685	1.678	1.673
Deviation from mean (per cent).....		-.3	-.1	+.4	.3	-.3
2608.....	91:71	2.604	2.616	2.627	2.616	2.60
2662.....	90:70	2.638	2.647	2.661	2.649	2.60
2865.....	92:72	2.567	2.579	2.615	2.587	2.56
2866.....	92:72	2.576	2.588	2.621	2.595	2.58
Mean.....		2.596	2.608	2.631	2.612	2.585
Deviation from mean (per cent).....		-.6	-.2	+.7	.5	-1.0
2608.....	101:71	3.832	3.848	3.864	3.848	3.85
2662.....	100:70	3.896	3.923	3.931	3.917	3.88
Mean.....		3.864	3.886	3.898	3.883	3.865
Deviation from mean (per cent).....		-.5	+.1	+.4	.3	-.5
2608.....	111:71	5.392	5.434	5.460	5.429	5.34
2662.....	110:70	5.501	5.554	5.585	5.547	5.45
2865.....	112:72	5.277	5.354	5.389	5.340	5.23
2866.....	112:72	5.304	5.355	5.415	5.358	5.30
Mean.....		5.368	5.424	5.462	5.418	5.342
Deviation from mean (per cent).....		-.9	+.1	+.8	.6	-1.4
2866.....	122:72	7.191	7.223	7.321	7.245	7.16
Deviation from mean (per cent).....		-.7	-.3	+1.0	.7	-1.2
2865.....	132:72	9.40	9.45	9.58	9.48	9.22
2866.....	132:72	9.46	9.52	9.63	9.54	9.38
Mean.....		9.43	9.48	9.61	9.51	9.30
Deviation from mean (per cent).....		-.9	-.3	+1.0	.7	-2.2

In order to determine later the agreement of the measurements on the lamps with those on the screens, percentage deviations from the mean obtained for all lamps at each voltage are given in Fig. 1, and the representative curve for each laboratory is drawn. The points at which the screens fall (i. e., the approximate voltage to which a tungsten test lamp would have to be set to obtain a color match with the screen removed) are indicated by the vertical

dotted lines which intersect the curves of this figure. Correction to the mean value of the transmission of each screen may now be assigned from a consideration of the percentage difference on the lamps, as shown in the figure at the intersection with the corresponding vertical line. There is thus obtained for the screens a relation among the laboratories corresponding to that given by the curves for the lamps over the range covered by the screens.

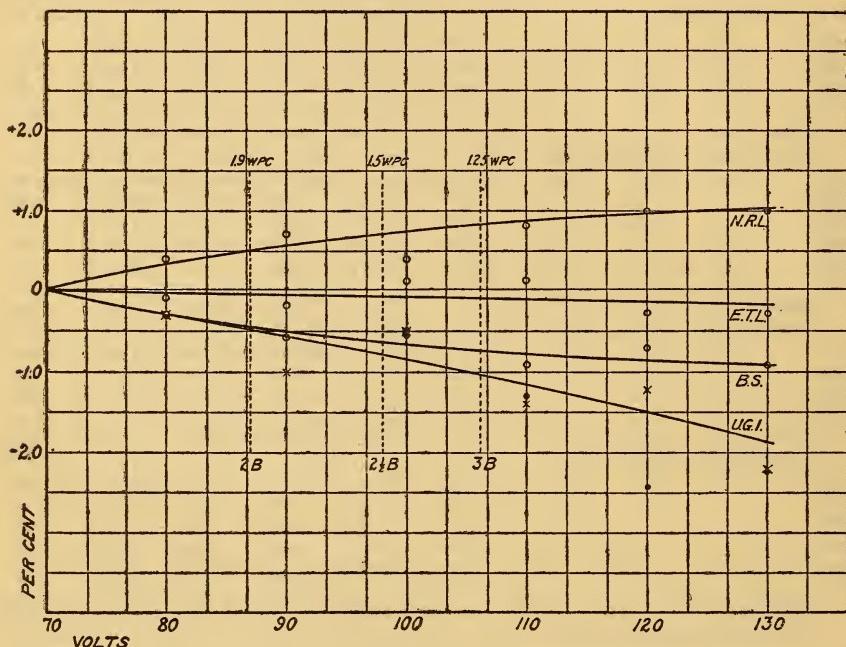


FIG. 1.—Values on the lamps expressed as differences from the mean obtained by the three laboratories using Lummer-Brodhun photometers. The dots at 100, 110, 120, and 130 volts represent flicker values found by Crittenden and Richtmyer. (See Section VI.)

VI. COMPARISON OF RESULTS ON LAMPS AND SCREENS

The values obtained for the glasses by direct measurement and those by computation (see Sec. V) from the results on the lamps are compared in Table 9. In the last four columns of the lower half of the table are the differences between these two sets of values. It is to be noted that for the three laboratories using the Lummer-Brodhun photometer the differences average about 0.2 per cent on the mean of the three glasses. That is, each laboratory was remarkably consistent in the two series of measurements.

TABLE 9

Comparison of Observed and Computed Values on the Screens

Screens	Values of screens as observed				
	B. S.	E. T. L.	N. R. L.	Mean	U. G. I.
2B.....	0.653	0.657	0.659	0.656	0.646
2½B.....	.584	.585	.588	.586	.579
3B.....	.537	.542	.543	.541	.529
Mean .....	.591	.595	.597	.594	.585

Screens	Relative values as computed from measurements on lamps				Differences, computed values from observed values			
	B. S.	E. T. L.	N. R. L.	U. G. I.	B. S.	E. T. L.	N. R. L.	U. G. I.
2B.....	0.653	0.6555	0.6595	0.6525	0.000	+0.0015	-0.0005	-0.0065
2½B.....	.5825	.5855	.5905	.5815	+ .0015	- .0005	- .0025	- .0025
3B.....	.537	.5405	.5455	.5355	.000	+ .0015	- .0025	- .0065
Mean.....	.591	.594	.5985	.590	.0005	.0012	.0018	.0052

In regard to the flicker values, it appears that the somewhat greater differences between the results on the glasses and the lamps is due to the values assigned to the former. As further evidence of this fact, the results by Crittenden and Richtmyer⁶ on two of the lamps (Nos. 2865 and 2866), using color screens calibrated by means of a flicker photometer, agree very closely, except at 120 volts,⁷ with those reported by the U. G. I., their values being indicated by dots in Fig. 1. On the other hand, the results given by the same authors for the screens by the flicker method do not agree so well with the U. G. I. values here reported.

The differences given in this table show that the first three laboratories mentioned are consistent in their measurements on the lamps and screens to within less than 0.2 per cent on the average, and that the U. G. I. computed value is practically the same as that of the Bureau of Standards.

VII. ADDITIONAL CHECK MEASUREMENTS

In order to secure a further check of the ratio of the values obtained by the Nela Research Laboratory and the Bureau of Standards, arrangements were made whereby F. E. Cady, through

⁶ Trans. I. E. S., 11, p. 331, 1916.⁷ These authors state that this value should not be given equal weight with the others because only one lamp was measured at this voltage.

the courtesy of Dr. Hyde, came to the Bureau and made a number of comparative measurements with the Bureau's observers who took part in this intercomparison.

Comparative measurements were first made of the ratio Y/B and of the transmission of a glass screen (3G) using the flicker photometer. (See next section.) In these measurements the B. S. observers checked their former values to within the errors of observation, and hence their values in this test are not here given. Following this test, one of the lamps (No. 2661) used in establishing the voltage-candlepower curve for tungsten lamps was measured at 106 volts in terms of its value at 70 volts using a Lummer-Brodhun photometer. At the latter voltage the color of this lamp was the same as that of a 4-wpc carbon and at the upper voltage the color corresponded to that produced by glass 3B when used with a 4-wpc carbon lamp. The comparison lamp was adjusted for color match with No. 2661 at 70 volts, and the illumination on the photometer screen was adjusted to 10 meter-candles as in all the previous measurements made at the Bureau in this intercomparison. Three series of determinations of the ratio of candlepower at the two voltages were made by five observers, including Mr. Cady, and all settings were made by the contrast principle as was done in all the previous measurements at the Bureau. These results, together with the values previously obtained for 3B by these five observers (see Table 5), each in his own laboratory, are given in Table 10.

TABLE 10
Comparison of Check Measurements

Observers	Series 1	Series 2	Series 3	Mean	Trans-mission of 3B, from Table 5
F. E. C.....	4.90	4.92	4.91	4.91	0.547
G. W. M.....	4.85	4.87	4.81	4.85	.542
J. F. S.....	4.79	4.84	4.81	4.81	.538
W. J. K.....	4.80	4.81	4.73	4.78	.534
G. J. S.....	4.80	4.76	4.73	4.77	.536
Mean of the four B. S. observers.....	4.81	4.82	4.77	4.80	.537 ₅
Value from B. S. voltage-candlepower curve.....				4.81	.538

A comparison of the last two columns shows that, for the lamp, the percentage difference between the value of Mr. Cady and the mean of the B. S. observers is practically the same as for the screen, although the latter was measured under considerably different conditions of illumination in the two laboratories. As the color step was the same in each case, it can be reasonably concluded from this check that the indicated small difference between the two laboratories is real and is due, at least in a great measure, if not entirely, to a difference in the characteristics of the two groups of observers. In this connection it is of interest to note that if, in either laboratory, the first half of the observers, in the order given in Table 5, be arbitrarily taken as one group and the other half as a second group, the difference between the value by the two groups in either laboratory is comparable with the difference between the laboratories themselves.

It is obvious, therefore, that all measurements involving a color difference should be left as much as possible to the standardizing laboratory where the observers should be carefully selected, their relation to normal determined, and, if necessary, corrections made to their observations.

VIII. CHARACTERISTICS OF THE BUREAU OF STANDARDS' OBSERVERS

In the investigation by Crittenden and Richtmyer, referred to in Section VI, the observers who took part in this intercomparison determined, with the flicker photometer, a value for the ratio of the Ives-Kingsbury yellow and blue solutions,⁸ and also a value for the transmission of glass screen 3G. These values, together with the values obtained with the Lummer-Brodhun photometer for glass screen 3B (Table 5, direct method), which had about the same color density as 3G, are given in Table 11. In this table are included also the mean values by the 114 observers used by Crittenden and Richtmyer, the values by Mr. Cady, and those by Dr. C. H. Sharp and Dr. H. E. Ives, who were observers in their respective laboratories and who visited the Bureau and made their measurements during the progress of the above investigation by Crittenden and Richtmyer.

⁸ Trans. I. E. S., 10, p. 203; 1915.

TABLE 11
Data on Observers

Observers	Ratio $Y+B$	Transmission		Deviations from average of 114 observers		Difference between deviations
		3G. Flicker photometer	3B. Lummer- Brodhun photometer	Flicker photometer	Lummer- Brodhun photometer	
G. W. M. (B. S.).....	1.025	.540	.542	-.003	+.008	+.011
J. F. S. (B. S.).....	1.103	.534	.538	-.009	+.004	+.013
B. M. (B. S.).....	1.120	.532	.526	-.011	-.008	+.003
H. B. S. (B. S.).....	.822	.559	.552	+.016	+.018	+.002
W. J. K. (B. S.).....	.968	.540	.534	-.003	.000	+.003
W. H. V. (B. S.).....	.948	.548	.535	+.005	+.001	-.004
A. H. T. (B. S.).....	1.014	.542	.535	-.001	+.001	+.002
G. J. S. (B. S.).....	.998	.540	.536	-.003	+.002	+.005
Means.....	1.000	.542	.537	-.001	+.003	+.004
F. E. C. (N. R. L.).....	1.044	.536	.547	-.007	+.013	+.020
C. H. S. (E. T. L.).....	1.058	.534	.537	-.009	+.003	+.012
H. E. I. (U. G. I.).....	.951	.542	.540	-.001	+.006	+.007
Average of 114 observers.....	.99	.543	.534	.....	.....	.....

It is to be noted that, although there is considerable variation in the ratio Y/B among the different individuals of the Bureau's group of eight observers, the mean of all is remarkably close to the characteristic ratio (0.99) found by Crittenden and Richtmyer for the average of 114 observers. Hence, as is evident from the results on 3G, a mean value obtained by this group with a flicker photometer would require practically no correction to obtain a value corresponding to that by the average eye.

A comparison of the values on 3B shows that this group is very close to the average of the 114 observers also in its results with the Lummer-Brodhun photometer, although not quite so close as with the flicker. Whether this slightly greater variation arises from the fact that in the average eye work of Crittenden and Richtmyer the illumination was higher than in this investigation, or that in the former the photometer was used as an equality rather than as a contrast field, or (as is more likely) from the greater uncertainty of the Lummer-Brodhun photometer, is difficult to say. However, as is shown by the differences between deviations and better by means of a plot between values of Y/B and transmission (Fig. 2), all the individuals of this group do not have, with respect to the average of the 114, the same relation with the Lummer-Brodhun photometer as they do with the flicker, the first two being decidedly different by the two methods.

Now it is found that if these two observers be omitted the mean of the other six with a flicker photometer is just as close to normal as the whole group, their mean flicker values for $3G$ and Y/B being 0.5435 and 0.98, respectively; and, further, their mean Lummer-Brodhun value for $3B$ is more nearly equal to the average eye value (0.534), being 0.536 instead of 0.537, as found by the whole group. It would appear, therefore, that in order to make a comparison of former B. S. values with present (average eye) values, as is done below, there is perhaps some advantage in using the mean of this "selected" group of six.

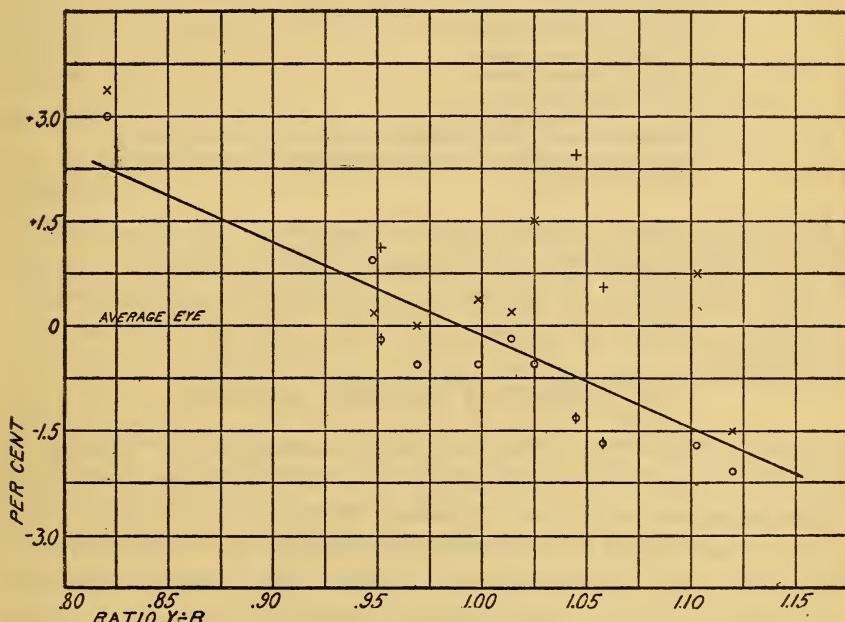


FIG. 2.—This is a plot of the values given in Table II. The ordinates are values of transmission expressed as differences in per cent from the corresponding average value obtained by 114 observers. Lummer-Brodhun values by the eight B. S. observers are represented by X's and their flicker values by o's. The corresponding values by the three observers from the outside laboratories are represented by +'s and φ's, respectively. The curve represents the flicker data obtained by the 114 observers.

Further checks on the value of $3B$ from the present investigation as well as from the investigation of Crittenden and Richtmyer, who determined values for $3G$, which was found to be 1.6 per cent higher than $3B$, are given in the following table. Nearly all of the 20 observers selected by Crittenden and Richtmyer from the 114 had considerable photometric experience, and they were well distributed with respect to the average eye characteristic as determined with a flicker photometer.

TABLE 12

Comparison of Values by Different Methods and also by Different Groups of Observers

I. With the Lummer-Brodhun photometer:	
A. As found in Crittenden and Richtmyer's investigation—	
1. By 114 observers selected at random from the Bureau of Standards scientific staff (one set each).....	3B = 0.534
2. By 20 observers selected from the 114 (two sets each).....	3B = 0.536
3. By 14 most consistent observers selected from the 20 (two sets each).....	3B = 0.538
B. As found in this intercomparison—	
1. By 8 observers.....	3B = 0.537
2. By 6 observers selected from the 8.....	3B = 0.536
II. With the flicker photometer:	
A. As found in Crittenden and Richtmyer's investigation—	
1. By 114 observers (same as above).....	3B = 0.534
2. By 20 observers (same as above)	3B = 0.534
3. By 14 observers (same as above).....	3B = 0.534
4. By 8 observers (same as above).....	3B = 0.533
5. By 6 observers (same as above).....	3B = 0.534
B. As found in this intercomparison—	
1. By U. G. I., direct measurement.....	3B = 0.529
2. By computation from U. G. I. measurements on lamps with the Lummer-Brodhun photometer and a Crova solution calibrated by a method involving the flicker photometer.....	3B = 0.536

From the above comparison it is apparent that for the color difference here represented the group of eight, as well as the group of six, is as nearly normal as it is possible for a small group to reproduce average eye values with the respective photometers mentioned.

IX. CHECK OF FORMER VALUES

Screen $2\frac{1}{2}B$ was chosen for this intercomparison because it had approximately the same color value as the glasses used in the intercomparison with the National Physical Laboratory. The mean values found for this screen by the group of eight and by the group of six were 0.5836 and 0.5828, respectively. The relative value of $2\frac{1}{2}B$ to $3\frac{1}{2}C$, which is one of the glasses used in the B. S.-N. P. L. intercomparison, has been recently determined and found to be as follows:

$$3\frac{1}{2}C = 2\frac{1}{2}B + 0.010$$

Therefore, by the group of 8 observers..... $3\frac{1}{2}C = 0.5836 + 0.010 = 0.5936$
 And by the group of 6 observers..... $3\frac{1}{2}C = 0.5828 + 0.010 = 0.5928$
 Value used in the B. S.-N. P. L. intercomparison in 1911..... 0.5924

Although in the earlier measurements made by the Bureau of Standards no method of selection of observers was employed and the illumination used was that employed in other work done at the Bureau and was much lower than that used in the recent investigation of Crittenden and Richtmyer, nevertheless it appears from the agreement in the above values that the considerable deviations from the mean of some of the observers at that time were such that the plus and minus deviations substantially coun-

terbalanced each other, and the figures then obtained by the Bureau with the Lummer-Brodhun photometer correspond closely to those now obtained by an average eye working under the higher illumination used by the investigators mentioned. Of course, it would not be expected that such deviations would all be in one direction, but that they were averaged out so completely was a matter of good fortune.

X. CONCLUSION

The results of this intercomparison show quite conclusively that in each laboratory, regardless of the kind of photometer used, even though a considerable color difference was involved, each observer maintained a fairly constant criterion with respect to the mean. The same is true of each laboratory in respect to its relation to the mean of all, as judged by the measurements on the glass screens and those made on the lamps some months afterward.

Considering the difficulties involved in the measurements, the different characteristics of observers and the wide difference in illumination employed, covering probably a range of ten times, the agreement among the laboratories must be considered remarkably good. It is true, however, that although the differences are small they are not negligible in precision photometry.

It is evident, therefore, that measurements to establish standards involving a color difference should be left as much as possible to the standardizing laboratory where the observers must be carefully selected and a considerable number employed and the kinds of instruments and the conditions of illumination, etc., definitely fixed.

An examination of the Bureau's observers who took part in this work shows that their mean characteristic is very approximately the same as that of the "average eye," as determined from a test of 114 observers taken at random from the Bureau's scientific staff.

Further evidence is obtained as to the accuracy of the values assigned to a group of 1.5-wpc tungsten standards used in a previous intercomparison with the National Physical Laboratory of England.

The authors express the Bureau's appreciation of the cooperation of the laboratories, and of those who represented them, in carrying out this investigation.

WASHINGTON, January 22, 1916.



